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TECHNICAL REPORT ECOM-2582

COMPARISON OF SOME PHYSICAL AND CHEMICAL PROPERTIES OF VACUUM EVAPORATED AND SPUTTERED NICKEL-CHROMIUM FILMS

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APRIL 1965

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DA TASK 1C0 24401 A 112 04

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ABSTRACT

Thin films of nickel-chromium were deposited on planar glass substrates by vacuum evaporation and sputtering processes. The alloy "Nichrome V" with a bulk composition Ni 80% Cr 20% was evaporated from a tungsten filament and used as the cathode in the sputtering process. The composition ratio, sheet resistivity, thickness, film density and temperature coefficient of resistance were investigated or derived for each process and compared.

Under constant deposition conditions the vacuum evaporated films indicate a variation of composition ratio with sheet resistivity whereas for sputtered films the ratio tends to remain more nearly constant over an extended range of sheet resistivities. The temperature coefficient of resistance varies with the sheet resistivity from positive to negative for the evaporated films whereas for the sputtered films the coefficient remains positive over an extended range of sheet resistivities.

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COMPARISON OF SOME PHYSICAL AND CHEMICAL PROPERTIES OF VACUUM EVAPORATED AND SPUTTERED NICKEL-CHROMIUM FILMS

INTRODUCTION

The use of nickel-chromium films for resistor application in thin-film circuitry is well established and developments are well advanced for use of these films as resistor elements on oxidized transistor grade silicon substrates for the fabrication of integrated circuits utilizing both passive and active elements.[1-6] These films are generally prepared by vacuum evaporation and in some cases by cathodic sputtering. It is known that the electrical and physical behavior of thin films are, in general, dependent upon the fabrication process, although in many cases quantitative data are lacking to explain the reasons for the variation of the film characteristics.

In this report an attempt has been made to find explanations for some of the differences encountered in the preparation of nickel-chromium thin-film resistors by both the vacuum evaporation and sputtering processes. It is hoped that the data and analysis presented will assist in leading to a better understanding of the various parameters which affect the physical and electrical properties of thin films, resulting in stricter control of the fabrication processes with a related improvement in the results.

EXPERIMENTAL PROCEDURES

Evaporation and Sputtering Conditions

Vacuum evaporations were carried out in an 18-inch bell jar within a pressure range of $1x10^{-5}$ to $1x10^{-6}$ Torr. The two evaporators used during the course of these investigations are shown in Figure 1. About 12% of a 1.2 gm charge of nichrome wire was evaporated from a 1/8-inch-diameter tungsten rod at temperatures between 1425°C and 1475°C in a typical deposition run. Four 1x3-inch glass slides occupying a total area of 5x3 square inches were mounted in a substrate holder. One slide was masked to serve as the resistance monitor and to provide a step for thickness measurement. A second slide without a mask was coated for subsequent chemical analysis. Each of the two remaining slides had masks through which 27 individual resistor strips were deposited. The average deposition rate was 2 Å/sec. The distance from the center of the tungsten rod to the center of the substrate holder was 9.5 inches.

Cathodic sputtering was done in a 16-inch bell jar within a total Argon pressure range of $2\text{-}4x10^{-2}$ Torr. A diagram of the internal arrangement of the bell jar is shown in Figure 2. The cathode consisted of an eight-inch-diameter nichrome disc 0.040-inch thick. After a vacuum of approximately $1x10^{-5}$ Torr was obtained, the bell jar was flushed with argon, this cycle being repeated three times. With the throttle valves closed, the argon leak valve was adjusted for a pressure rise of about one micron per second. The throttle valve was then partially opened and adjusted to balance the inflow of argon at an approximate pressure of $3x10^{-2}$Torr. The power supply was adjusted to deliver 3500 volts with the pressure being maintained to pass a current of 60-80 ma. Four 1x3-inch glass slides were positioned 2½ inches below the cathode on a plate with non-conducting legs, with the plate being elevated 3 inches above the base plate. A shutter was utilized to shield the substrates during the first 30 minutes of sputtering so that any films deposited thereafter would be free from any contamination. Typical deposition rates under the prescribed conditions were 1-3 Å/sec. Monitoring was conducted on a 1/8-x 3-inch glass strip which consisted of 16 squares between land areas on which outside leads were welded.

Cleaning and Masking Processes

The substrate material utilized for the nickel-chromium depositions was soda-lime soft glass. The glass slides were cleaned in an ultrasonically agitated detergent bath, followed by tap water rinsing, then placed in a sulphuric acid-chromate cleaning solution which was brought to a temperature of 100°C and then allowed to cool. Following a distilled water rinse, the slides were treated with 1% HF solution (quick rinse), rinsed again with distilled water with the excess water being blown off with unheated, filtered compressed air and finally passed through the oxidizing flame of a Meeker burner. This procedure was based on previously reported experimental work wherein it was determined by electron micrograph studies that HF treatment was necessary to remove chemical residues and grease which still remained fixed to a layer of silica on the glass surface after a chromic sulphuric acid cleaning.[7] The flaming of the slide was another step to ensure

complete elimination of organic films of any kind; however, this process has been discontinued since the flaming of a slide can result in a blemished surface of one kind or another. This same heat cleaning effect can be obtained by a furnace treatment at 400°C.[8]

Film patterns were obtained either by suitable masking during the vacuum evaporation process or by etching away the unwanted film parts after removal from the sputtering chamber. The masks used for the vacuum evaporation process were made of 3-mil-thick nickel-plated beryllium copper with slot widths of 5,10,20 and 40 mils accurate to within ± 0.2 mils. The length of all resistance strips prepared was 240 mils between land areas (made of silver manganese).

Similar patterning of the sputtered films was accomplished by photolithographic means. Working transparencies were prepared by reducing parallel strips to 10-, 20-and 40-mil- width black lines on Kodalith films. The sputtered nichrome films were coated with a positive type resist and exposed through the transparency. Immediately after development and rinsing the slides were etched at room temperature in a freshly prepared bath of the following composition: Conc. HCL 10 ml., ammonium persulfate 2 gm. and water up to 100 ml. Complete solution of the thickest films prepared required no more than 2 to 3 minutes. After complete etching, the slides were thoroughly rinsed in tap water and the remaining resist was dissolved off the metal strips with acetone. The particular resist used required no post baking. Its developer was an aqueous solution thereby resulting in a relatively simple rinsing procedure.

All samples prepared by the two deposition processes were subjected to a post deposition aging treatment which consisted of a 4-hour static heat treatment in air at 200°C.

<u>Film Thickness and Chemical Analysis</u>

Thickness measurements were made using Tolansky's well-known multiple beam interference method.[9,10] An interferometer attachment was designed and built to fit on a microscope objective and was used for generating interference fringes. The width of the interference fringes proper, although narrow compared to the fringe-to-fringe distance, was still such as to impose a limit on the reliability of thickness determinations in the extreme low range ($<$ 100 Å). When possible a double step (groove) was used which was created during deposition by masking with a wire in contact with the substrate since gradual tapered edges result in inaccurate measurements.

Spectrophotometric methods were used to make the micro-determinations of the nickel and chromium content in both vacuum evaporated and sputtered films. For the determination of nickel the dimethyl - glyoxime oxidizing reagent method [11] was used and the absorption of the solution measured at the wavelength of minimum transmission (4750 Å). For the determination of chromium the diphenyl carbazide method [12] was used and the absorption measurements were made at a wavelength of 5400 Å. Calibration curves were established for absorbence versus known concentrations of nickel and chromium (Figure 3).

For the actual measurement, the deposited nickel-chromium film was completely dissolved off its glass substrate and subjected to chemical treatment according to the prescribed procedure after which the absorbence was measured of the unknown nickel or chromium content and the weight (mass) was read from the respective calibration curve. The quotient of the 2 figures represents the composition ratio r (by weight) for the two metals.

By the described analytical procedure, the nichrome material used in the two deposition processes indicated the following composition:

Nichrome wire for evaporation:	Ni	79.82%
	Cr	19.66%
	Ni	79.88%
Nichrome for cathodic disc:	Cr	20.19%

Measurement of Film Resistance

Measurements included sheet resistivity, ρ_s, (ohms per square) before and after static heat treatment with a Leeds & Northrup Wheatstone Bridge #5430A; resistance change with dependence upon a temperature cycle in the range between -30°C and 125°C. Each sputtered film was measured with a four-point probe [13,14] after removal from the chamber and prior to the patterning process. The probes were made of tempered spring steel with ground points set at 0.03" on centers and were contained in a detachable head mounted on a two-directional micro-manipulator for ease in positioning. Electrical connections were made at the center of the completely coated glass slide by pressing the four probes against the film surface. By suitable adjustment of the measuring circuit, the ratio $K_r = \frac{V}{I}$ was determined for each sputtered film. Resistivity measurements were then made for these same films after the patterning had been completed and the sheet resistivity was calculated. The ratio and sheet resistivity were correlated and the relationship K_r (ρ_s) over the range of 8 to 1200 ohms/square is shown in Figure 4.

RESULTS AND DISCUSSION

Fractionation - Evaporation and Sputtering

It is well known that most of the conventional evaporation techniques used in the vacuum deposition of nichrome result in some degree of fractionation of the alloy. Techniques are available which may provide better composition control including evaporation of metals from separate sources, evaporation of the charge to completion, flash evaporation, and evaporation from a solid state after distribution of concentrations in solid phase has become stationary; [15] however, each one of these processes is limited in so far as practical application is concerned.

It can be predicted qualitatively that the composition of the film resulting from the vacuum evaporation of an alloy as described in this report will differ from that of the source bulk material because of unequal volatilization of the components. For example, the value of the relative evaporation rates (E) for the two metals in a binary compound can be roughly

estimated by dividing their $P/M^{\frac{1}{2}}$ ratios (P = vapor pressure of the pure metal, M = molecular weight) and multiplying by the weight ratio (W) so that

$$\frac{\Sigma_A}{\Sigma_B} = \frac{W_A\ P_A\ M_B^{\frac{1}{2}}}{W_B\ P_B\ M_A^{\frac{1}{2}}}\ .$$

At 1200°C $P/M^{\frac{1}{2}} = 1.27 \times 10^{-3}$ Torr for chromium and 3.68×10^{-6} Torr for nickel [16], which indicates that for 80:20 nichrome the chromium will vaporize about 75 times faster than the nickel at that source temperature.

The sputtering of materials composed of more than one element, i.e., alloys and compounds has not generally been studied in detail.[17] Information is lacking which indicates how much fractionation of nichrome occurs during the cathodic sputtering process; however, a comparison of the sputtering rates of different metals (after Guntherschulze), measured under constant conditions of cathode fall (V = 770 volts) and current density, within a hydrogen atmosphere, show that for chromium the rate is 27 mg./amp. hour whereas for nickel it is 65 mg/amp. hour.[16] A certain deviation from the bulk material could then be expected in the sputtered film because of the unequal sputtering rates of the metals since the sputtering yields of alloys should follow those of their main constituents.[18,19] Indicative of such behavior were films of nickel-iron deposited by sputtering from solid permalloy (Ni 81% Fe 19%) cathodes in an argon atmosphere.[20] Analysis of the sputtered films by X-ray fluorescence probe technique indicated that the average Ni composition was 79.75%. The sputtering rate for iron in hydrogen atmosphere is 68 mg/amp. hour[16] as compared to the figure of 65 for nickel previously mentioned.

Film Composition

In the past several years a number of researchers have been concerned with the fractionation of alloy films and have conducted investigations on this to varying extents.[20,21,22,23,24,25] Except for Siddal who has used chemical microanalysis to relate the change in percentage of chromium in the deposited film with change in source temperature, they have resorted in their investigation to X-ray emission spectrography, X-ray fluorescence probe technique or to electron diffraction analytical procedures.

For the studies as discussed herein, the microanalytical methods were utilized as described previously which permitted the establishment of the following relationships for both vacuum evaporated and sputtered nichrome. Figure 5 illustrates the correlation between the sheet resistivity ρ_s and the nickel chromium ratio, r, wherein r = 4 for the starting material. Figure 6 illustrates the relation between the sheet resistivity and the weight - percent chromium ($\frac{1}{1+r}$) and nickel ($\frac{r}{1+r}$). For Figure 6 the assumption is made that the film is composed of only nickel and chromium so that the sum of the nickel plus the chromium content always adds up to 100%. The trend of the results and range of their validity are clear; for vacuum evaporated films the higher the sheet resistivity, the richer is the chromium

content (up to 95%) and the lower the nickel content whereas for sputtered films the results were confined to a relatively limited range, that is, the chromium content of the film varied between 18-10% with a related nickel content of 82-90%. The line of demarcation between the processes is well defined; in no case did the vacuum evaporated films reach the ratio 4 of the starting bulk material whereas for the sputtered films none was formed with a ratio less than 4.4. The observed scattering which is more pronounced for the vacuum evaporation process is due both to deviation from constancy of the critical evaporation and deposition parameters and to certain inaccuracies in the techniques of determining r. The most stable vacuum evaporated films, which are in the range of 10 - 150 ohms/square have a chromium content of 30 to 50% while for sputtered films of the same sheet resistivities the chromium content is in the range of 12-18%.

__Sheet Resistivity, Film Thickness and Temperature Coefficient of Resistance__

A functional relationship between the film thickness and sheet resistivity ρ_s (t) was established for the nickel-chromium films prepared by the vacuum evaporation process as described previously. This relationship indicates that for these vacuum evaporated films the range of thicknesses varies from approximately 50 Å up to 4000 Å with related sheet resistivities of 3600 to 3 ohms/square. It is the thicker films with low sheet resistivities that approach the nickel chromium ratio of the starting nichrome material whereas the thinner films with higher sheet resistivities had ratios as low as 0.05.

Thickness measurements for the sputtered films ranged from approximately 65Å up to 700Å with related sheet resistivities of 200 to 15 ohms/square. A comparison of the ρ_s (t) relationship for the two processes is shown in Figure 7. Thickness measurements could not be determined for sputtered films with sheet resistivities above 200 ohms/square because of the limit of accuracy of the apparatus; however, from the data obtained and as shown in Figure 7, it appears that sputtered nichrome would more nearly follow the theoretical function ρ_s (t), at least in the range of 10-100 ohms/square, where $\rho_s = \frac{\rho_B}{t}$ (ρ_B = 108 μ ohm-cm).

Resistor samples were prepared from the deposited films with a wide range of sheet resistivities and subjected to temperatures in the range of -30°C to 125°C to determine the temperature coefficient of resistance. The temperature coefficient, α, as a function of the sheet resistivity, ρ_s , is shown in Figure 8 and is summarized below:

	(ppm/°C)	range (ohms/sq)
Evaporated Films	From +350 to +50	3 to 20
	= + 50	20 to 600
	0 to -3 00	600 to 3000
Sputtered Films	150 ± 40	5 to 1200

The apparent formation of mixed oxide and metal (see film density below) during the formation of the film with high sheet resistivities ($\gtrsim$600 ohms/square) by the vacuum evaporation process could be an explanation for both the measured low and negative temperature coefficients. (Some further comments on the negative temperature coefficient are discussed below)

The relatively smooth transition of α through zero (samples were fabricated with 0 coefficients) becoming slightly positive over an extended range of ρ_s (20-500 ohms/square) and then rising relatively rapidly below 10 ohms/square suggests how the true metallic electronic conductivity begins to predominate as the effect of the oxide content is decreased with increasing film thicknesses. From these observations, it would be of interest to obtain an indication of the degree of oxidation occurring in a film under the described deposition conditions since varying amounts of chromium and nickel oxides built into the film may play a more influential part than does the fractionation in controlling the final resistivity. However, the actual quantitative determination of the oxide content in a thin film is a relatively difficult task and no such data are available although some qualitative work has been done which has indicated the actual presence of Cr_2O_3 in films prepared during the vacuum evaporation of nichrome.[21] For the sputtered films it is reasonable to assume that the films are basically metallic since one means of defining either a metal or alloy is by a positive temperature coefficient of resistance.

Aging Effects

Post - deposition heat treatment of the deposited film stabilizes the film to its final nominal resistance value. During the heat treatment the film is relieved of high internal stresses, defects in the crystal lattice are reduced and the formation of a protective oxide layer is made more complete.[26] The 4-hour heat treatment was selected since it had been determined that after the initial change, prolonged heat treatment at 200°C caused no appreciable resistance change, at least in the sheet resistivity range of 150 ohms/square, and thermal cycling of the film up to 125°C and back to ambient room temperature indicated no hysteresis.

The percent resistance change due to heat treatment as a function of sheet resistivity for vacuum evaporated and sputtered nichrome is shown in Figure 9. A slight decrease in resistance is noted for the vacuum evaporated films with sheet resistivities below 10 ohms/square; from 10-100 ohms/square there is a slight increase with a more rapid rise as sheet resistivities increase. The sputtered films tend to follow the same pattern but with two differences, these being a larger increase in resistance occurring at lower sheet resistivities and considerable scattering existing for the higher sheet resistivities.

Film Density

The film density (g/cm^3) was calculated from data obtained in the course of chemical analysis. A steadily decreasing density from 8.0 to 3.5 with increasing sheet resistivity (5-140 ohms/square) and related decreasing thicknesses (3000-200Å) was calculated for the evaporated films (Figure 10). For the sputtered films, densities were relatively constant and more nearly like that of the starting alloy varying between 7.2 and 9.0 over a sheet resistivity range of 30 to 140 ohms/square. These results are indicative of the mixed oxide and metal content of the thinner vacuum evaporated films with the effect of the less dense oxides decreasing as film thickness increases.

On the other hand for sputtered films the densities tend to remain more nearly like that of the starting alloy over the range for which calculations were made. Reference values (g/cm^3) for the bulk material are: 8.9 for nickel, 8.2 for 80/20 nichrome, 7.2 for chromium, 7.45 for NiO and 5.2 for Cr_2O_3.

Theoretical Models

Neugebauer,[27] Hartman[28] and Bashara,[29] among others have presented recent theoretical models to explain the conduction mechanism of thin metallic films. All have assumed that below a certain film thickness (< 100 Å, more likely several tens of Å thick), these films consist of a planar array of small discrete islands. Bashara has used a model originally formulated by Frenkel and has assumed that the conduction is thermally activated with the conductance being proportional to the number of charge carriers (electrons) which surmount the barrier energy between the islands. Neugebauer's model consists likewise of a large number of metal islands with the charge carrier being thermally activated; however, the charge transfer between particles occurs by tunneling. Hartman's model is based on the electrical conduction mechanism of tunneling in discontinuous metal films by transitions from an excited level of one particle to the corresponding level in the next, provided the applied electric field is small. Each of these models makes the prediction that conductance increases with temperature accounting therefore for the negative temperature coefficient displayed normally by very thin evaporated metal films.

Feldman[30] has explained the transition between thick continuous films with positive temperature coefficients and thin granular or lacunary films with negative coefficients by combining the linear resistance of the individual grains (ρ grain) and the resistance due to the gaps or potential barriers (ρ gap) so that the total resistivity (ρ) of the film is:

$$\rho = \rho_{gap} + \rho_{grain}.$$

Between the two extreme ranges in thickness there is an apparent transition region where one might expect to find zero or very low coefficients. It can be seen that the vacuum evaporated nichrome films as described in this report tend to follow this model qualitatively.

In general it should be noted that the theories advanced are considered highly idealized. Many assumptions and approximations must be made to permit relatively simple results which shall permit some order of accuracy; however, the actual system being approximated is very complex and good quantitative agreement might be obtained only with considerably more detailed theoretical models. However, there are many variables (see below) that come into play in determining the final characteristics of a thin metal film (and more so for an alloy) so that one can readily agree with Hartman that further considera-tion of a more detailed system is probably not warranted considering the wide variation in the films regarding specific details. In addition, although a number of models have been suggested as mentioned herein, the microphysical basis for the decrease in resistance with temperature is still not well understood.

It has been postulated that the low and negative temperature coefficient associated with the relatively thin (< 100 Å) vacuum evaporated films may be due to an extent to the relatively large proportion of chromium and nickel oxide built into the film; likewise film discontinuities may be the major cause for the negative coefficient below a certain thickness. At any rate, all the models discussed are suitable to describe the general physical behavior of these thin films.

The sputtered nichrome films contrary to normal observed thin film behavior have retained positive coefficients over a sheet resistivity range of 10-1200 ohms/square, with films with a sheet resistivity of 200 having thicknesses in the order of 65 Å. (The negative temperature coefficient of metallic films below a certain thickness, ≈ 50 Å, is well established experimentally 29). One can surmise that the sputtered nichrome films with sheet resistivities up to 1200 ohms/square would be several tens of Å thick yet still be continuous as indicated by the positive temperature coefficient and thereby not following the general behavior of thin metallic films.

According to Feldman, the exact thickness at which the film's structure becomes continuous depends primarily on the material used and the temperature of deposition. Based on the results obtained during this study, it would appear that the method of deposition plays a significant part in determining the thickness at which the film becomes continuous.

A thin metal film may possess a smooth texture if the forces binding the condensed atoms to the substrate are greater than or comparable to those forces between the condensed atoms.(16) In this respect it is interesting to compare the relative energies and related velocities imparted to the atoms, which form the final films, by the vacuum evaporation and sputtering processes. Recent results(31) obtained for a copper surface sputtered by 1000 eV Kr ions indicated average energies of 9.5 eV ($v = 5.38 \times 10^5$ cm/sec) for the ejected atoms. For atoms evaporated at the same rate (5×10^{17} atoms/sec-cm^2) and requiring a source temperature of about 1500°K, the average energy is 0.26 eV ($v = 8.9 \times 10^4$ cm/sec). A source temperature of 55000°K would be required to provide evaporated atoms of 9.25 eV average energy.

Variables Determining Sheet Resistivity and Temperature Coefficient of Resistance

This report has been concerned mainly with chemical composition and its related effect on deposited nickel-chromium films; however, there are other variables which are responsible for determining the final resistivity and the temperature coefficient of metal alloy films. Some of the most influential variables, all of which determine, to some degree, the final characteristics of the films prepared during the vacuum evaporation or sputtering process include: film thickness and structure, film uniformity and continuity, crystallographic structure, rates of evaporation or sputtering, pressure, source - substrate geometries and the substrate structure, smoothness, cleanliness, temperature and thermal expansion characteristics. Each one of these has been studied to some extent under controlled conditions. In addition the effect of each variable need not be the same

for each deposition process. It has been shown in this report that this is particularly true in so far as the fractionation of the bulk alloy is concerned. This in turn further magnifies the problem when one attempts to set up a model which can be utilized to interpret quantitatively the physical behavior of thin metallic films. Nevertheless, the empirical data gathered during the past several years for vacuum evaporated and sputtered nichrome films has permitted a better understanding and control of these deposition processes. It is now well known that although deposited nickel-chromium films (particularly when vacuum evaporated) do not possess the properties of the bulk material, the films can still be prepared with reproducible characteristics provided that the deposition conditions are kept as constant as possible.

CONCLUSIONS

1. A comparison of the vacuum evaporation and cathodic sputtering processes for depositing nichrome films indicates that fractionation of the starting bulk alloy occurs during both processes to varying degrees.

2. For the vacuum evaporation process the nickel-chromium ratio varies with the sheet resistivity; whereas for sputtered films the ratio tends to remain more nearly like that of the starting bulk material.

3. The temperature coefficient of resistance of vacuum evaporated films varies with the sheet resistivity from positive to negative; the temperature coefficient of resistance of sputtered film, while exhibiting some variation, is always positive showing that such films retain their metallic characteristics over an extended range of sheet resistivities.

4. The film density for vacuum evaporated films decreases with increasing sheet resistivity whereas the density for sputtered films remains relatively constant and more nearly like that of the starting material.

ACKNOWLEDGMENTS

The authors acknowledge gratefully the efforts of Mr. J. McCarthy in conjunction with the data acquisition.

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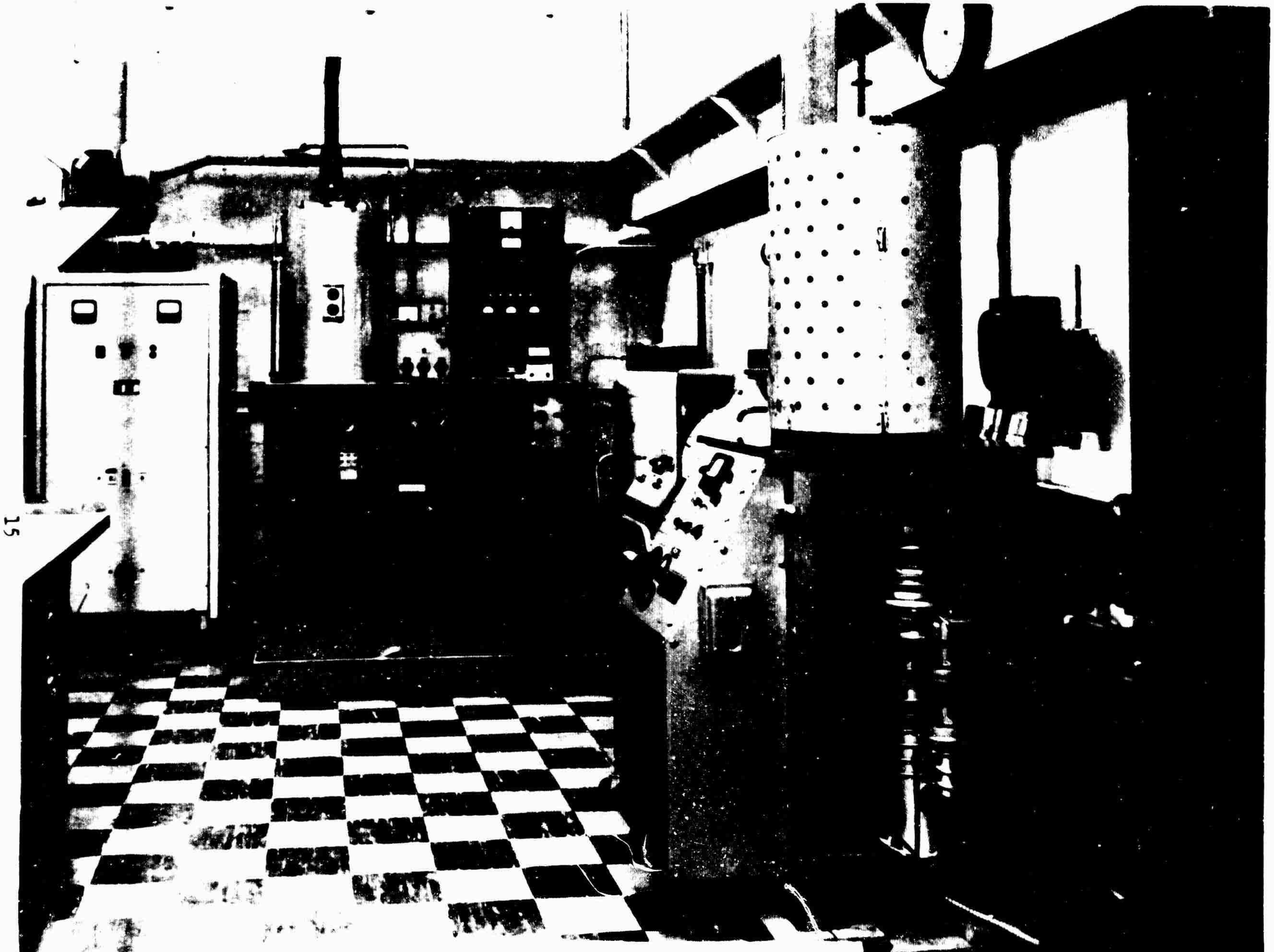

FIG. 1 VACUUM EVAPORATORS AND AUXILIARY EQ

A CATHODE
B GLOW SUPPRESSION SHIELD
C SUBSTRATES
D WORK HOLDER
E INSULATED LEGS FOR WORK HOLDER
F ROTARY SHUTTER
G PYREX TUBE ISOLATORS
H ALUMINUM SUPPORT AND CONDUCTOR FOR CATHODE
J BASE PLATE - ANODE

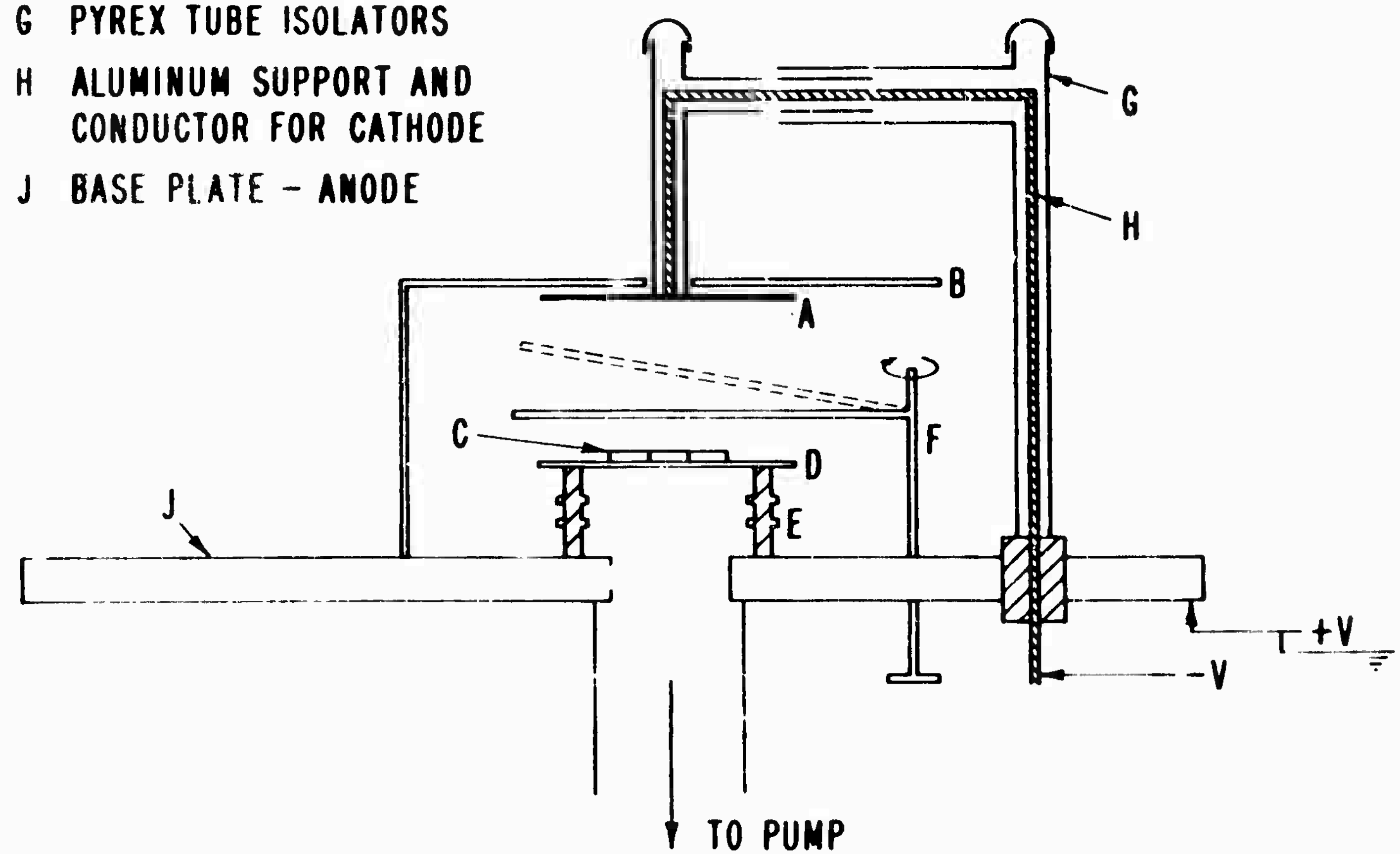

FIG. 2 INTERNAL ARRANGEMENT OF BELL JAR OF SPUTTERING UNIT

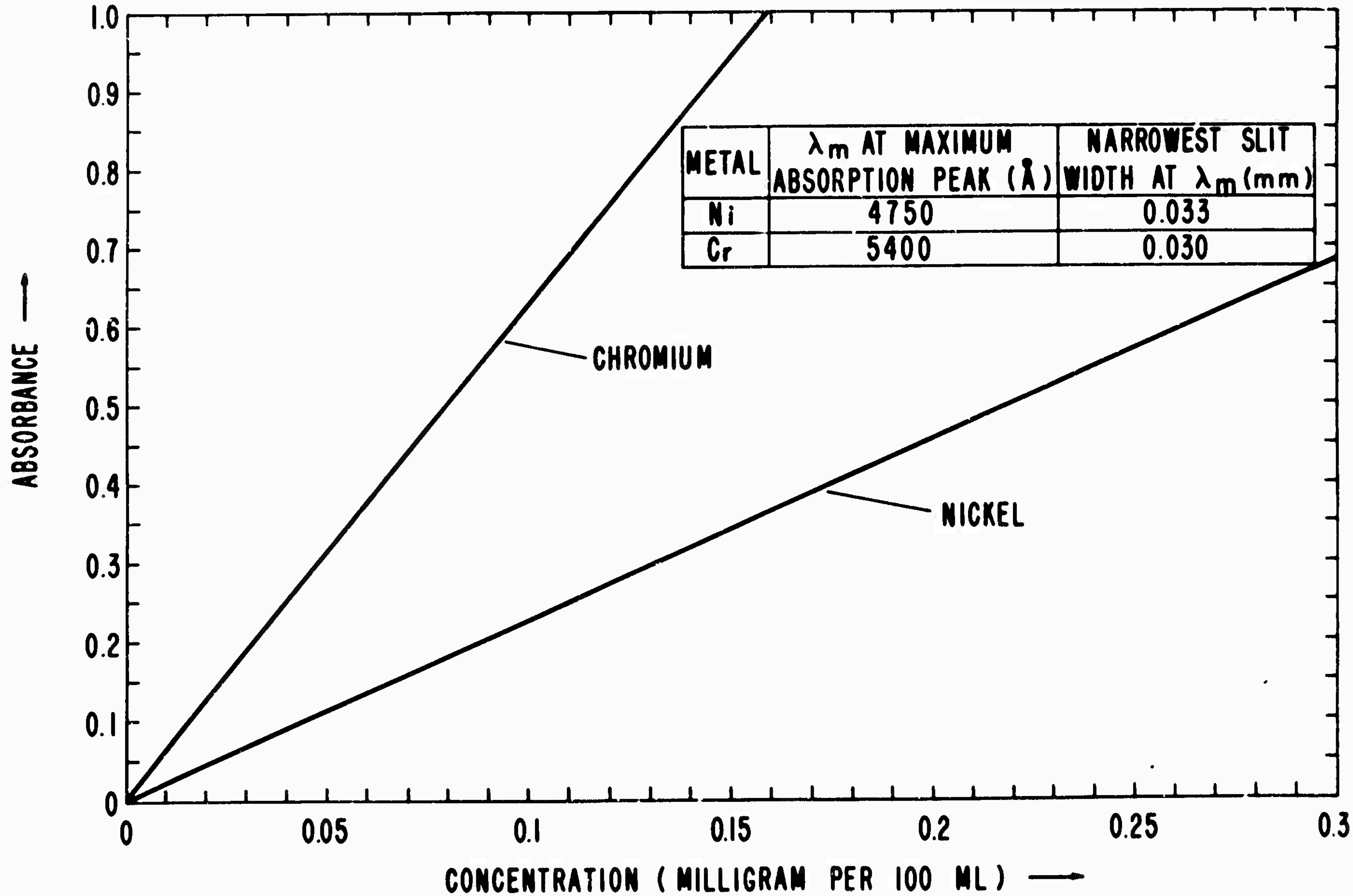

FIG. 3 ABSORBANCE VS. CONCENTRATION
(CALIBRATION FOR CHROMIUM AND NICKEL)

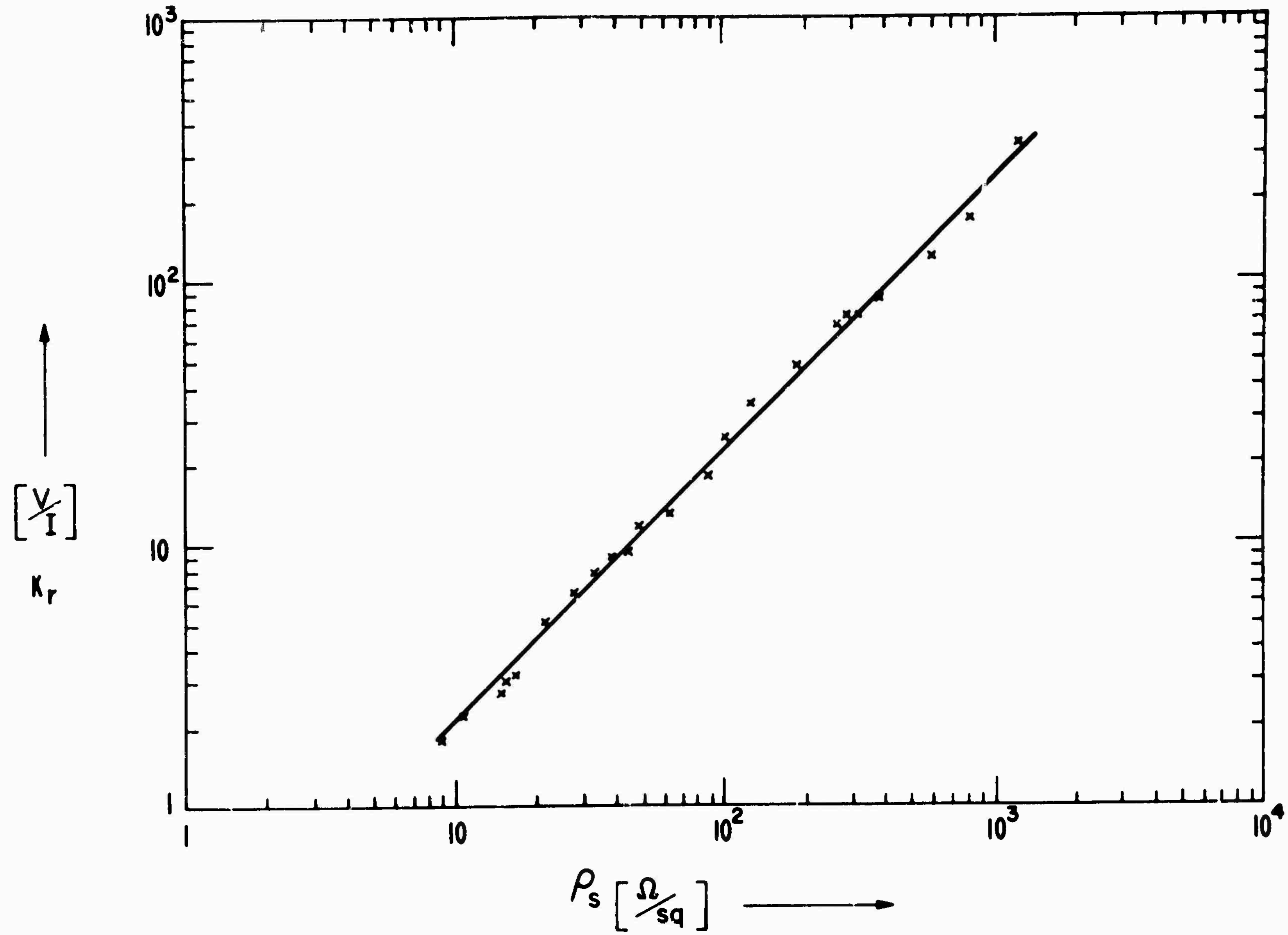

FIG. 4 CORRELATION BETWEEN 4 POINT PROBE RATIO K_r & THE SHEET RESISTIVITY ρ_s OF SPUTTERED NICHROME

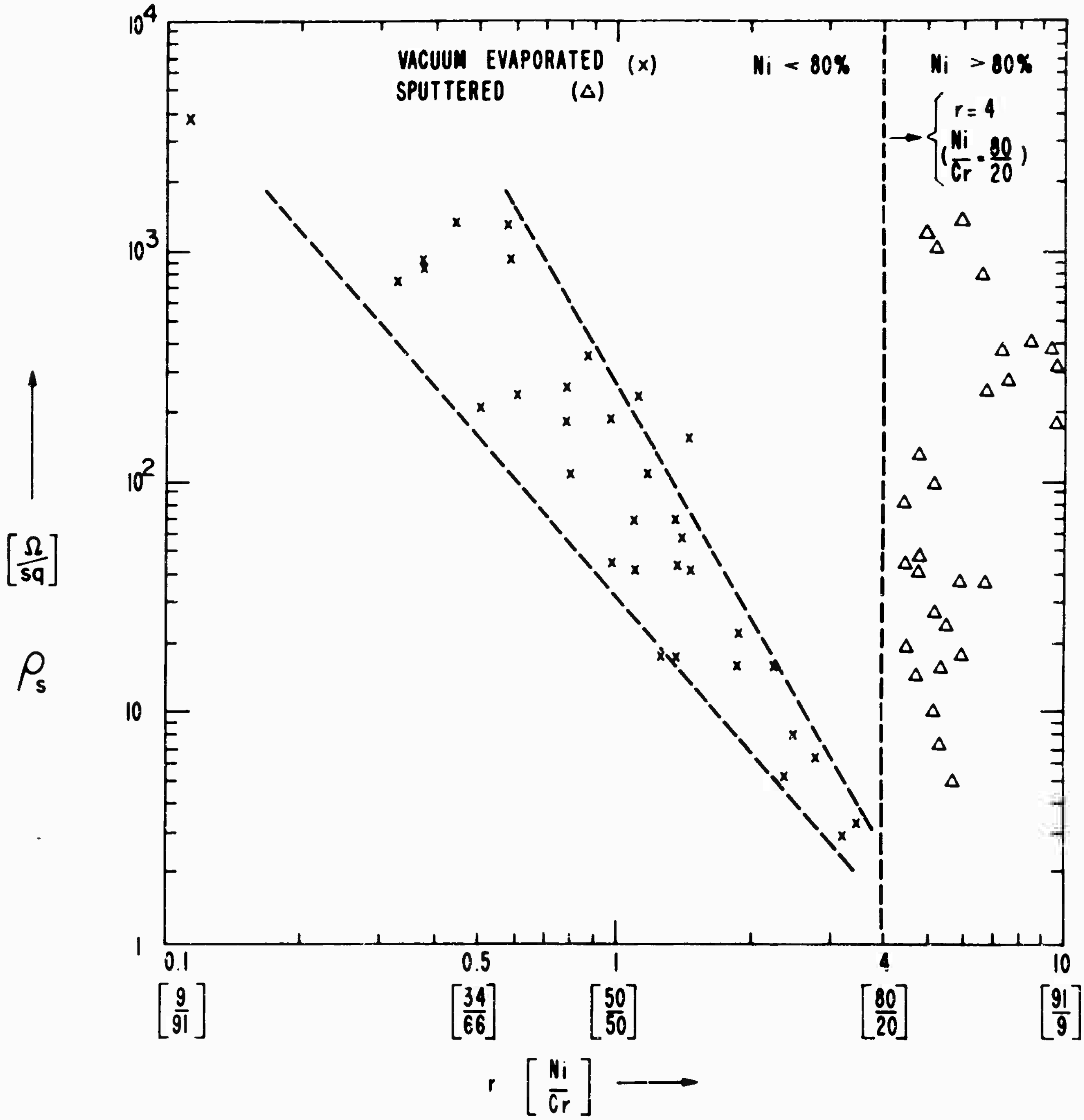

FIG. 5

CORRELATION BETWEEN SHEET RESISTIVITY ρ_s & COMPOSITION RATIO r (BY WEIGHT) OF VACUUM EVAPORATED & SPUTTERED NICHROME

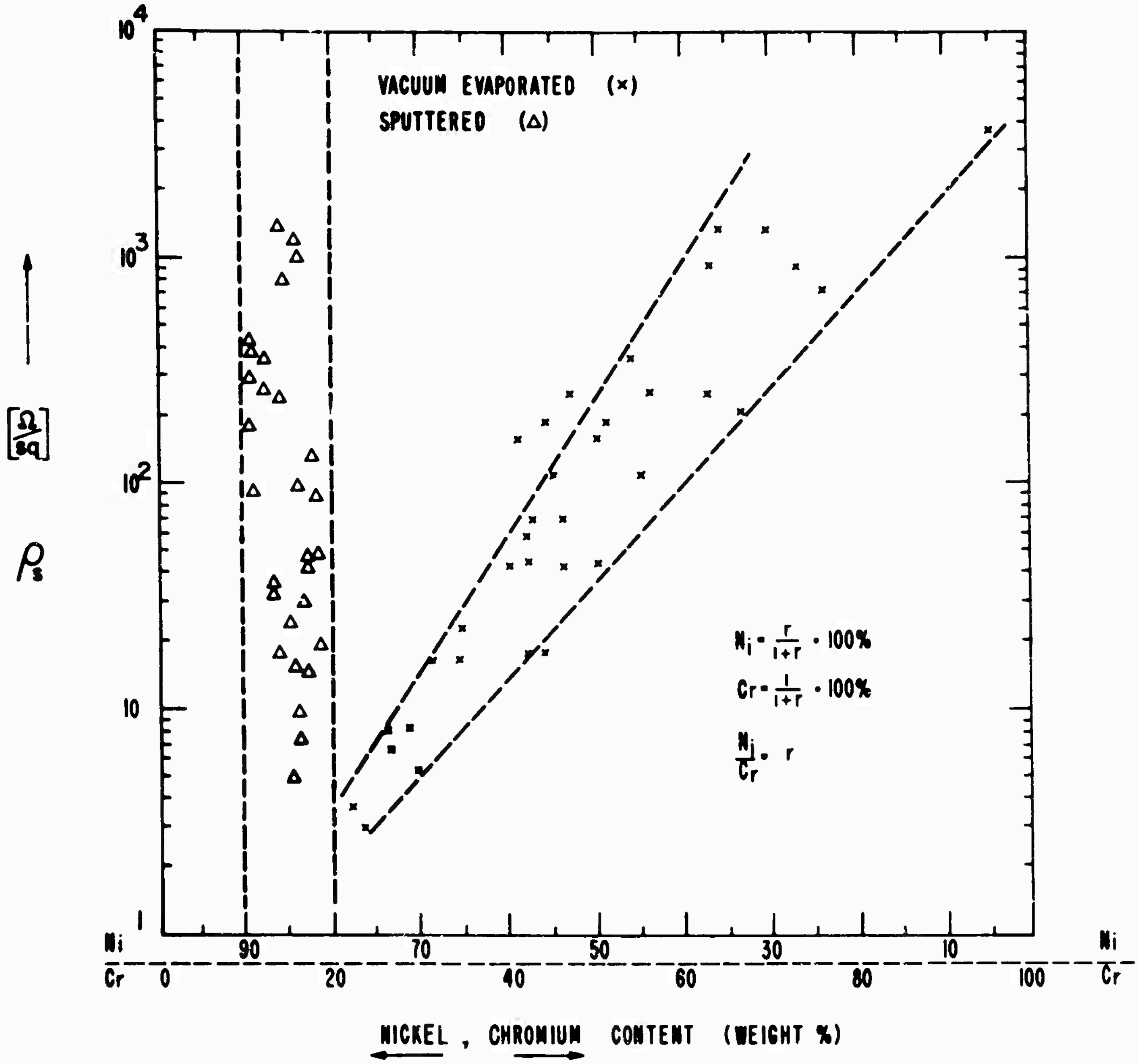

FIG. 6

CORRELATION BETWEEN SHEET RESISTIVITY ρ_s & % WEIGHT COMPOSITION OF VACUUM EVAPORATED & SPUTTERED NICHROME

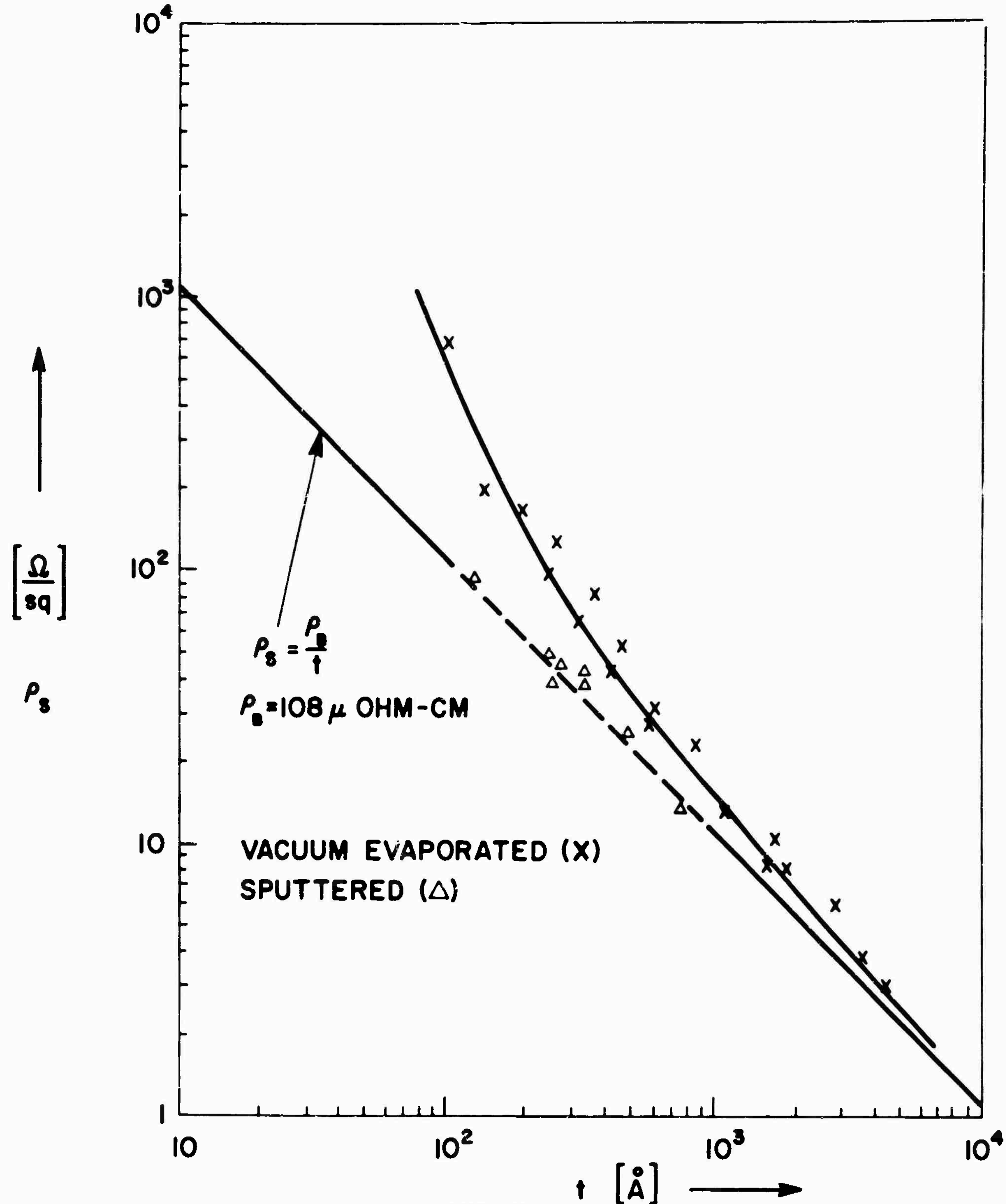

FIG. 7

DEPENDENCE OF SHEET RESISTIVITY ρ_s UPON FILM THICKNESS t FOR VACUUM EVAPORATED AND SPUTTERED NICHROME

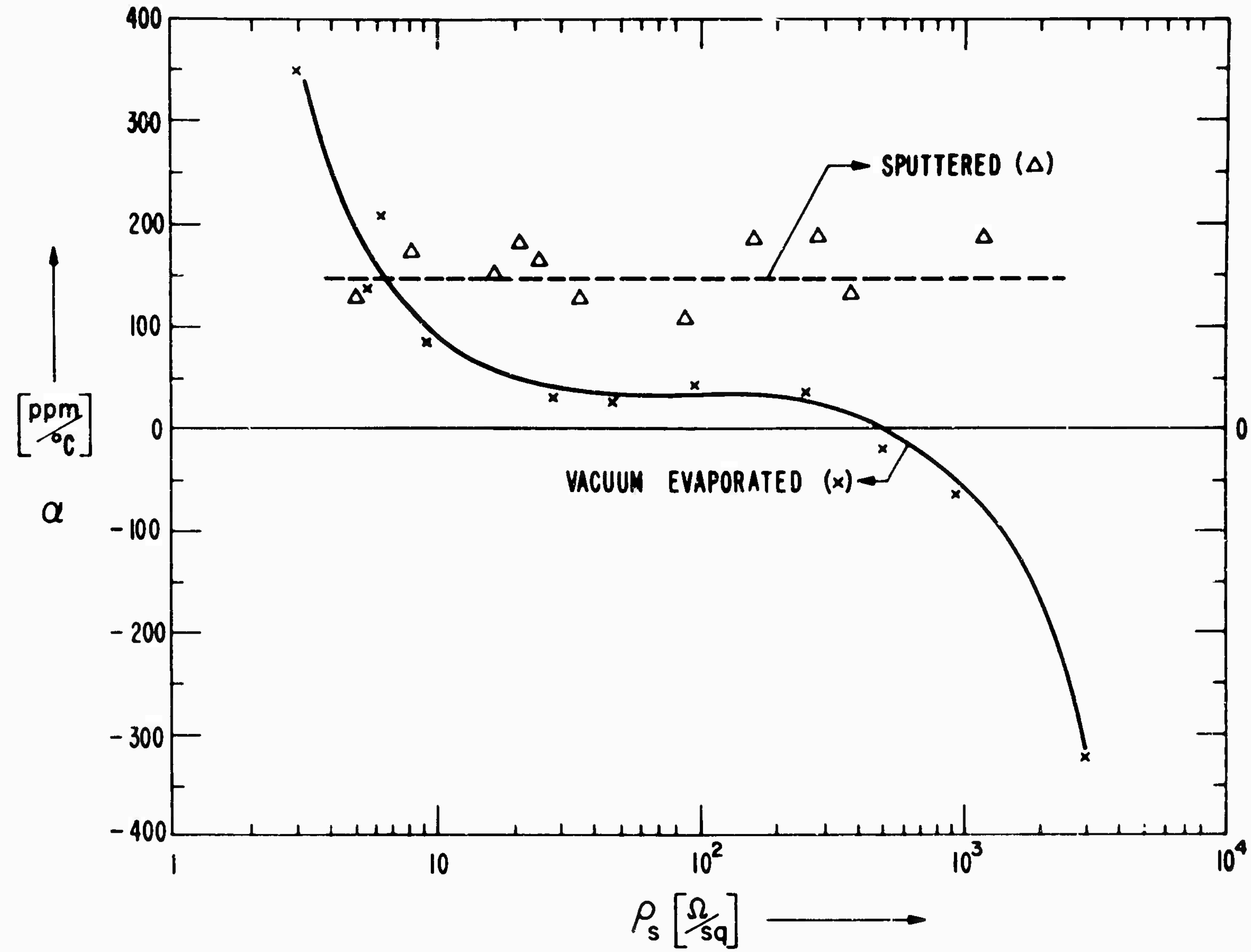

FIG. 8

TEMPERATURE COEFFICIENT OF RESISTANCE α AS A FUNCTION OF SHEET RESISTIVITY ρ_s OF VACUUM EVAPORATED & SPUTTERED NICHROME

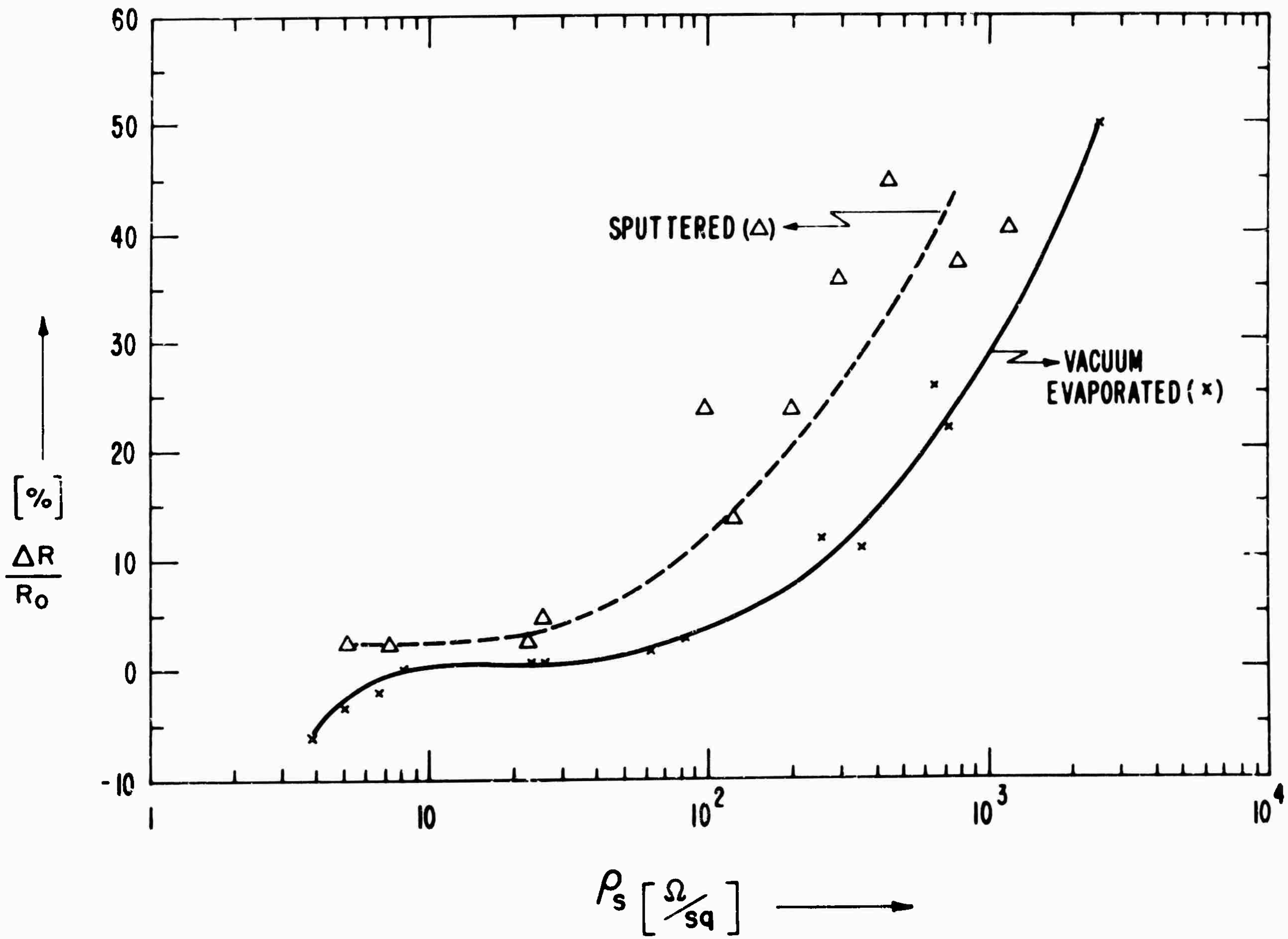

FIG. 9

PERCENT RESISTANCE CHANGE DUE TO HEAT TREATMENT AS A FUNCTION OF SHEET RESISTIVITY FOR VACUUM EVAPORATED AND SPUTTERED NICHROME

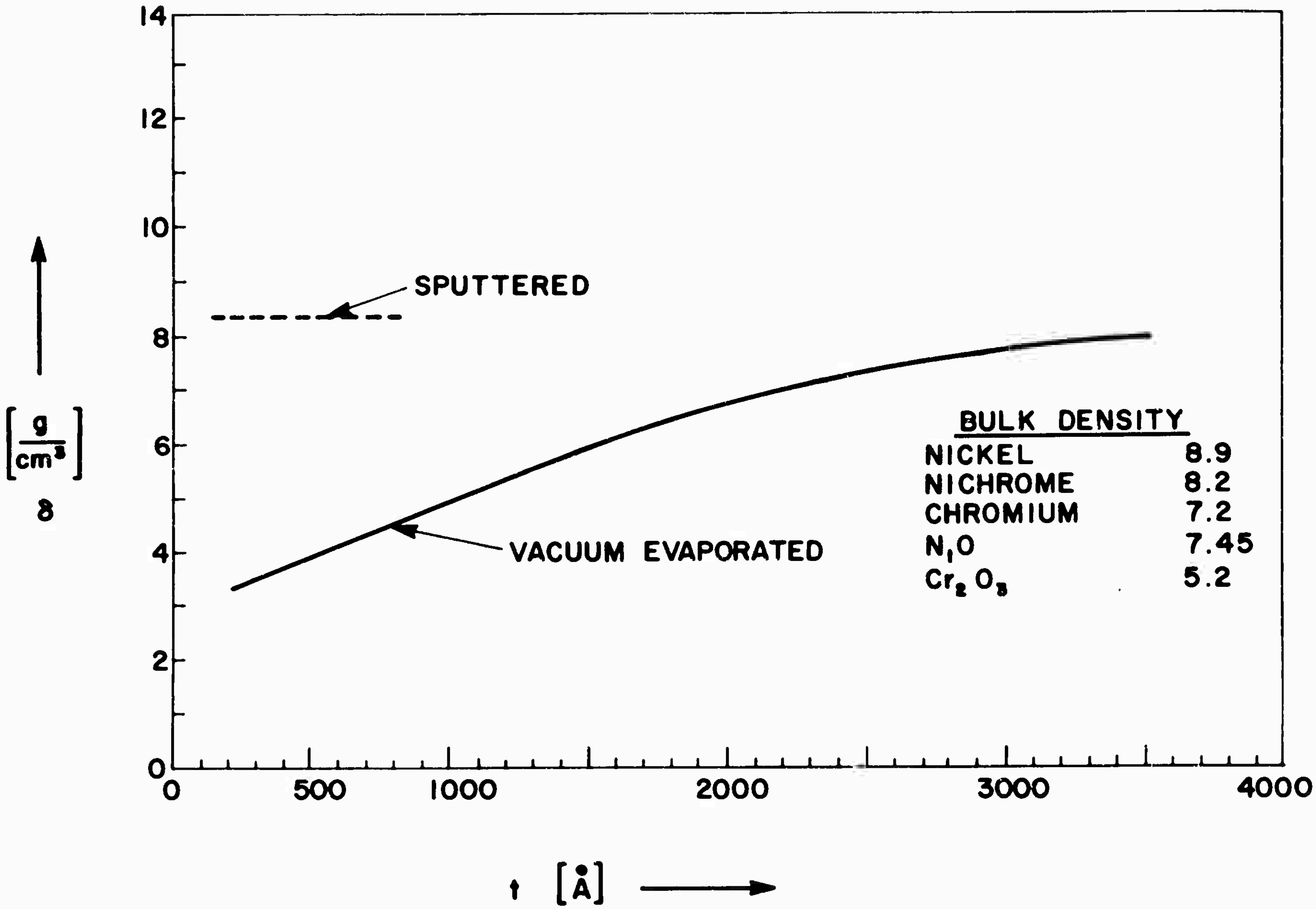

FIG. 10

DENSITY-THICKNESS DEPENDENCY δ (t) IN NICKEL-CHROMIUM FILMS (ON GLASS SUBSTRATE)